A STUDY OF
RUTHENIUM 106 AS A BETA SOURCE IN
RADIATION THERAPY

Russell B. Buchanan, Jr.
Captain, U. S. Army
Radiological Defense Engineering Prog
1951

A STUDY OF RUTHENIUM 106 AS A BETA SOURCE IN RADIATION THERAPY

A Thesis

Presented in Partial Fulfillment of the Requirements

for the Degree Master of Science

By

RUSSELL BENNETT BUCHANAN, JR., B. E. E.

The Ohio State University

1951

Approved by:

William G. Myers, Advisor

TABLE OF CONTENTS

A STUDY OF RUTHENIUM 106 AS A BETA SOURCE IN RADIATION THERAPY

INTRODUCTION

It is the purpose of this paper to present a study of the properties of the radiations emitted by Ruthenium 106 and its daughters as applied to the therapy of the external lesions of cancer, various warts and moles, and such other surface disturbances of the body as may be responsive to irradiation.

The generally accepted current medical practice is to treat these abnormal conditions by surgery (excision or cauterization), by the use of various chemotherapeutic agents (very limited in number and scope), or by irradiation of the affected area when other methods are not considered practicable. Surgery and, to a lesser degree, chemotherapy are frequently considered impracticable[6] for a number of reasons:

1. The position of the growth renders surgical approach difficult without high mortality or crippling risk.
2. The growth may be too extensive.
3. Metastases may be present.
4. The poor general health of the patient due to cardio-vascular or renal disease, obesity, or debility from old age.

5. The patient may, for his own reasons, refuse surgical treatment.

According to statistics compiled by the Swedish Cancer Association, only one-third of all cancerous conditions coming under medical supervision are suitable for surgery; and, of those who undergo surgery, only one-third (1/9 of the total) show other than temporary, short-lived relief. One must also consider all of the noncancerous conditions, many of which are not suitable for surgery. It is, therefore, frequently necessary to employ one or more of the various methods for radiation therapy. Currently, the most commonly employed radiation sources are X-ray machines and radium for gamma and/or beta-ray treatments. Any of these methods involve essentially the same hazards as are found in the deep irradiation therapy of malignant growths which cannot be reached by the short-range beta particles. This is true even of the radium beta ray applicators since the beta-emitting daughters of radium are maintained in equilibrium with those emitting gamma rays, and thus produce a deep irradiation field which is unnecessary in the treatment of surface lesions, and is undesirably detrimental to the normal tissues of the patient and to the health of the attending physician. The successful treatment of any malignant or disfiguring growth by irradiation depends upon the administration of a quantity of radiation sufficient to produce permanent arrest of the growth without causing extensive damage to the underlying normal tissue which is essential to proper repair. Where usable, surface

irradiation has the distinct added advantage in that no surgical or anaesthetic risks need be taken.

Fortunately, during the treatment of a surface lesion, the X-ray or gamma ray dose received by both the patient and the radiologist is not normally sufficient to induce either the acute or the chronic type of radiation sickness. The patient, having received his treatment, leaves the radiation field and, therefore, discontinues his exposure. This is not true of the attending physician, however, for he must also expose himself during the preliminary preparations for a treatment and again afterward in returning the source used to its place of safe storage (when sources other than X-ray machines are used). In addition, it must be considered that a busy radiologist will expose himself in this same manner many times during a single day, and that this daily exposure is continued throughout the year. The proof that many of these doctors do receive an injurious dose leading to chronic radiation injuries may be seen in the large number of radiologists and dentists who have been compelled to undergo amputation of fingers, and even of hands, in the malformed fingernail structure of others, and in the frequently observed pigmentation changes, leukemias, aplastic anemias, and high incidence of carcinoma observed in pioneer radiologists[4]. It has definitely been shown that chronic exposure to nuclear radiations, even at low dose levels, is carcinogenic[6].

It is, therefore, essential to develop some new source or sources of mildly penetrating radiation for treatment of these

surface lesions, which will not include the serious gamma-ray hazard incidental to the use of radium sources for beta particles. Another advantage of employing beta ray sources other than radium derivatives is the elimination of the gas-leak hazard, which is so dangerous in radium work. For this purpose, many investigators have been examining the table of isotopes, particularly those fission products available in relatively large quantities from nuclear reactors, in an effort to find beta-emitting materials with a suitable penetrating power and half-life, with a minimum of electromagnetic radiation. Of the various isotopes investigated to date, the current favorite is the strontium 90-yttrium 90 family, of which the effective beta particle has a maxiumum energy of 2.2 Mev. However, with appropriate filtering to eliminate the low energy 0.63 Mev particle emitted by Sr 90, the intensity of the radiation field falls to 50% of the surface dose in 0.8 millimeters of tissue(16), as shown in Figure 7. Since the effective penetrating depth in soft tissue of this beta particle is fairly low, and, therefore, only very superficial lesions will be reached by it, it is desirable to find some other beta source which possesses a greater penetrating power, thereby requiring a lower total surface exposure to the lesion to achieve the same therapeutic result. This would provide an appreciable reduction in tissue necrosis and the resultant ulceration and secondary infection, as well as a better cosmetic effect, as the lesion heals.

surface lesions, which will not include the surface [illegible] [illegible] incidental in the use of radium sources for beta particles. Another advantage of employing beta ray sources other than radium derivatives is the elimination of the gas-leak hazard, which is so dangerous in radium work. For this purpose, many investigators have been examining the table of isotopes, particularly those fission products available in relatively large quantities from nuclear reactors, in an effort to find beta-emitting materials with a suitable penetrating power and half-life, with a minimum of electromagnetic radiation. Of the various isotopes investigated to date, the current favorite is the strontium 90-yttrium 90 family, of which the effective beta particle has a maximum energy of 2.2 Mev. However, with appropriate filtering to eliminate the low energy 0.61 Mev particle emitted by Sr 90, the intensity of the radiation field falls to 50% of the surface dose in 0.8 millimeters of tissue(16), as shown in Figure 7. Since the effective penetrating depth in soft tissue of this beta particle is fairly low, and, therefore, only very superficial lesions will be reached by it, it is desirable to find some other beta source which possesses a greater penetrating power, thereby requiring a lower total surface exposure to the lesion to achieve the same therapeutic result. This would provide an appreciable reduction in tissue necrosis and the resultant ulceration and secondary infection, as well as a better cosmetic effect, at the lesion [illegible].

Since high-energy beta particles impinging on the metallic portions of the applicator holders currently in use produce a rather high Bremsstrahlung flux, it is also desirable to develop holders which will minimize this effect. In addition, the applicators should be designed in such a manner as to provide for easy mounting on the patient without requiring the physician to hold them in place as is the case with the current Sr 90 applicators.

It is with these factors in mind that this study, designed to explore the advantageous physical properties of Ru 106 with a view to the advantageous utilization of them in radiation therapy, was initiated. Included herein are data showing the intensity distribution of the beta field surrounding various Ru 106 sources in tissue equivalent phantoms, information concerning the relative X-ray and gamma ray output when the emitter is electroplated on various plating bases, some information on the physiological effects, as well as methods for measuring the penetration of beta particles in tissue phantoms.

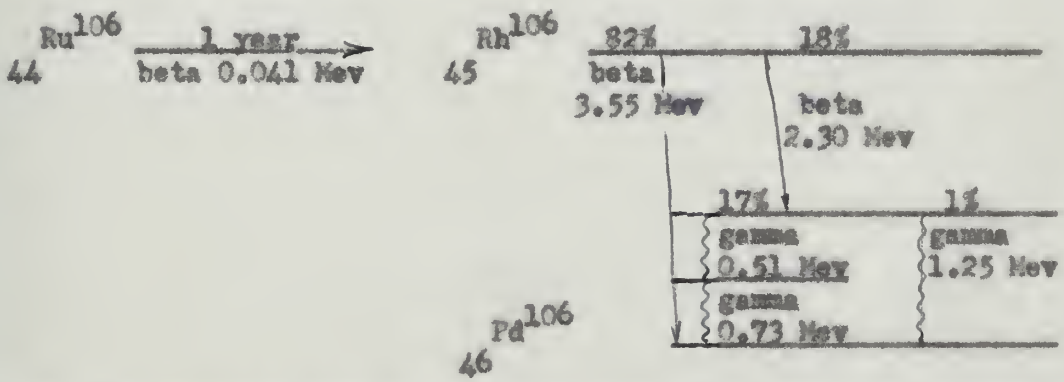
EXPERIMENTATION

Equipment

Ruthenium Sources Employed:

Ru 106 was selected as a possible radiation source for this work due to the conveniently high energy of the beta particle from the daughter element Rh 106, the comparatively constant output incidental to its one year half-life, the extremely low gamma-ray output relative to a radium source of the same beta intensity, and due to the absence of any gas-leakage problem. In addition, ruthenium, unlike strontium[20], does not deposit in the skeletal structure when accidentally ingested.

The decay scheme of the Ru 106 family is[33]:



The beta particle from Ru 106 is of very low energy. That portion which is not eliminated by self absorption within the source proper can be readily screened out of the effective radiation field by a thin plastic film which will not appreciably attenuate the desired beta field. This may be readily seen by comparison

of the range of the two particles. The 3.55-Mev particle has a range of 1.924 gm/sq cm, while the 0.041-Mev particle has a range of less than 0.004 gm/sq cm.

As part of the general aim of this project, an effort was made to determine the relative levels of Bremsstrahlung emission from the various plating bases. For electron energies in the neighborhood of 100 Kev, the efficiency of conversion of electron energy to X-ray energy is directly proportional to the atomic number. That this is not directly applicable to electrons of higher energy is substantiated by experimental work now in progress at the laboratories of the General Electric Company. However, indications are that the final relationship, when developed, will show that the conversion efficiency for these higher energy electrons will be some function of the atomic number of the target material, such that the use of a target of low atomic number will produce less X-ray output than will targets of high atomic number. Gold, copper, and beryllium were selected for study in this aspect.

The specific Ru 106 sources employed in this study were furnished from the Isotopes Division, Oak Ridge National Laboratory. Since ORNL does not specify the exact quantity of material provided in any shipment of this nature, the amounts specified herein are only within the accuracy of the information provided on the shipping papers from ORNL.

<u>Source 1</u>: 2 mC Ru 106 electroplated on a gold disc 0.01 inch thick and 1 inch in diamter. Experimental evidence encountered

in these tests showed that the Ru 106 was not uniformly plated thereon (Figure 1). Data was not taken from this disc due to the unsatisfactory nature of the emitting surface.

<u>Source 2</u>: 3 mC Ru 106 electroplated on a copper disc 0.01 inch thick and 1 inch in diameter. Again, experimental evidence showed a lack of uniformity in plating the sample on the disc (Figure 2), although this sample was sufficiently satisfactory to permit the taking of data therefrom. It is believed that both samples were probably plated on material which had not received adequate preparation and, possibly, at too high a deposition rate.

Fig. 1. Source 1.
Autoradiograph of source in applicator holder. Note the uneven plating of the Ru 106.

Fig. 2. Source 2.
Autoradiograph of source in applicator holder. Note that the Ru 106 is more evenly plated here.

<u>Source 3</u>: This source has not yet been delivered from ORNL. It has been requested that 3 mC Ru 106 be plated on a beryllium disc 1 cm thick and 1 inch in diameter. Although beryllium is a difficult and hazardous material with which to work[26], it was selected as the material with the lowest atomic number with which to carry out these tests satisfactorily. The range of the

3.55 Mev beta particle in beryllium is 11.1 mm. Since this beryllium disc should be covered with about 1 mm of Al as a convenient handling case, essentially all the beta rays from this source will be completely stopped within the source proper. This will eliminate any beta hazard from back radiation to the radiologist who may be called upon to manipulate it, and will also make the applicator a convenient size and weight to be fastened directly to the area to be irradiated. The light-weight feature is highly desirable in that, although surface growths of the type to be treated with this applicator are not normally supplied with neural fibers, pressure on the lesion transferred to the surrounding tissue can cause the patient considerable discomfort.

Electronic Circuits:

The electronic circuit employed in this study is one designed by A. O. Nier(31) for use in a mass spectrograph, and modified for use as a d.c. amplifier with miniature ionization chambers by D. T. Eggen, who also did the initial construction work on the instrument. Dr. Eggen's modification merely consisted of employing one channel of Dr. Nier's circuit and modifying the filament supply of the amplifier to provide the proper current for half as many tubes in series.

Since the equipment had been in dead storage for some time prior to the beginning of this project and had been rather

badly mishandled during that period, it was necessary to rebuild a large portion of the system before it could be placed in operation. In applying this instrument to the work with ruthenium, it was necessary to introduce an additional 100,000 ohm resistor into the feedback and metering circuit in order to desensitize the system to the point where it could properly handle the signal strength obtained.

For the assistance of others who may employ this system, operating voltages are shown on the circuit in Figure 3. Caution must be used to insure that the high voltages are not applied to the preamplifier until its cathode has had at least thirty seconds to warm. It is also advisable to permit the entire electronic system to warm for several minutes to establish the stability required for this work. Shielding is necessary on the cable from the preamplifier to subsequent stages as there is enough cable pickup to make the unshielded system unstable. It is also necessary to establish an electrical connection between the mercury-water system (see discussion of phantom) and the amplifier, since the changing electric field and static charge developed while the mercury is flowing will otherwise drive the meter off scale, requiring several seconds for the system to discharge. For this purpose, it is recommended that the connection be made to the outer electrode of the chamber for the additional reasons discussed under ion chamber windows.

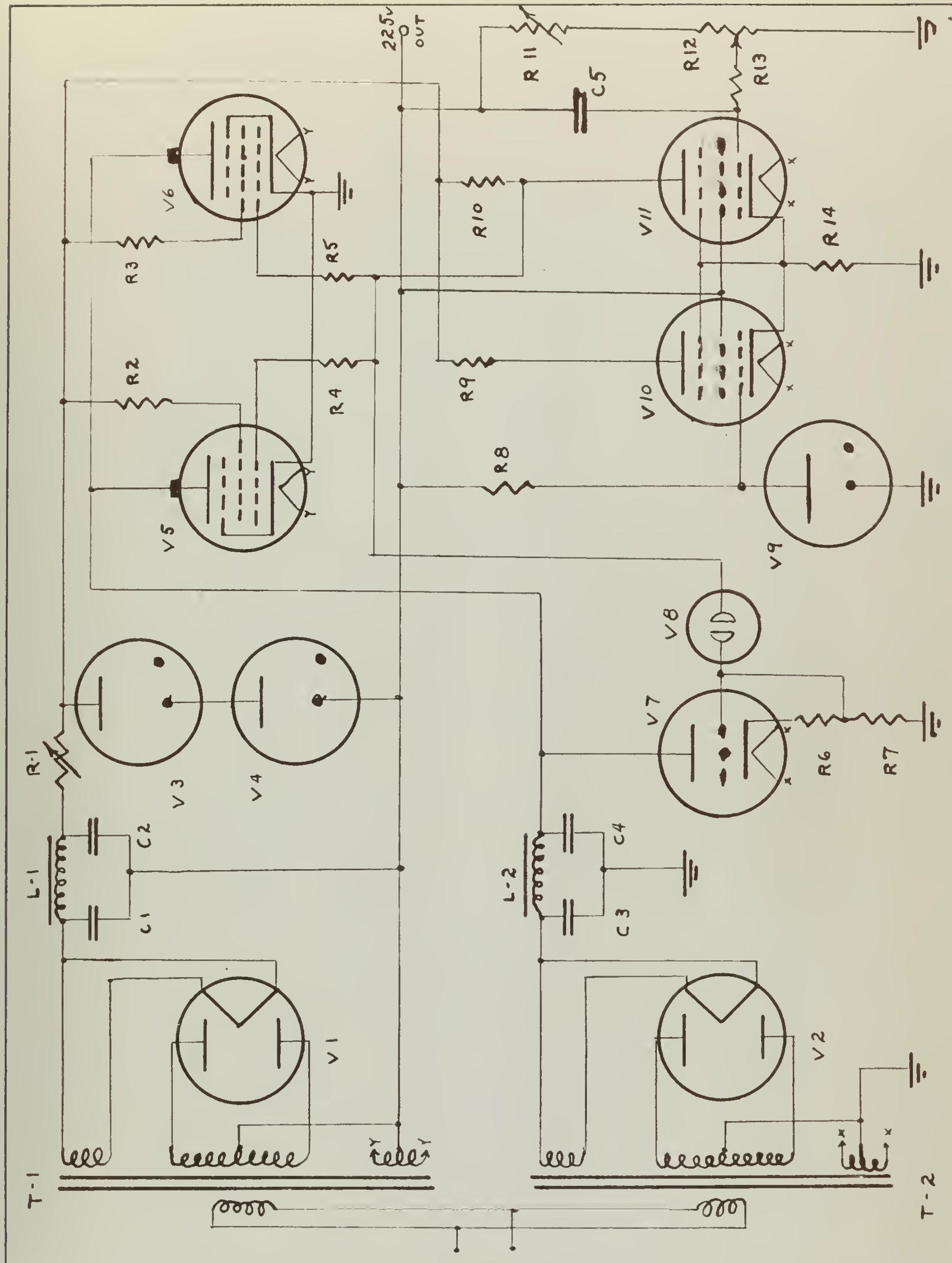


Fig. 3a: Power Supply Circuit Diagram

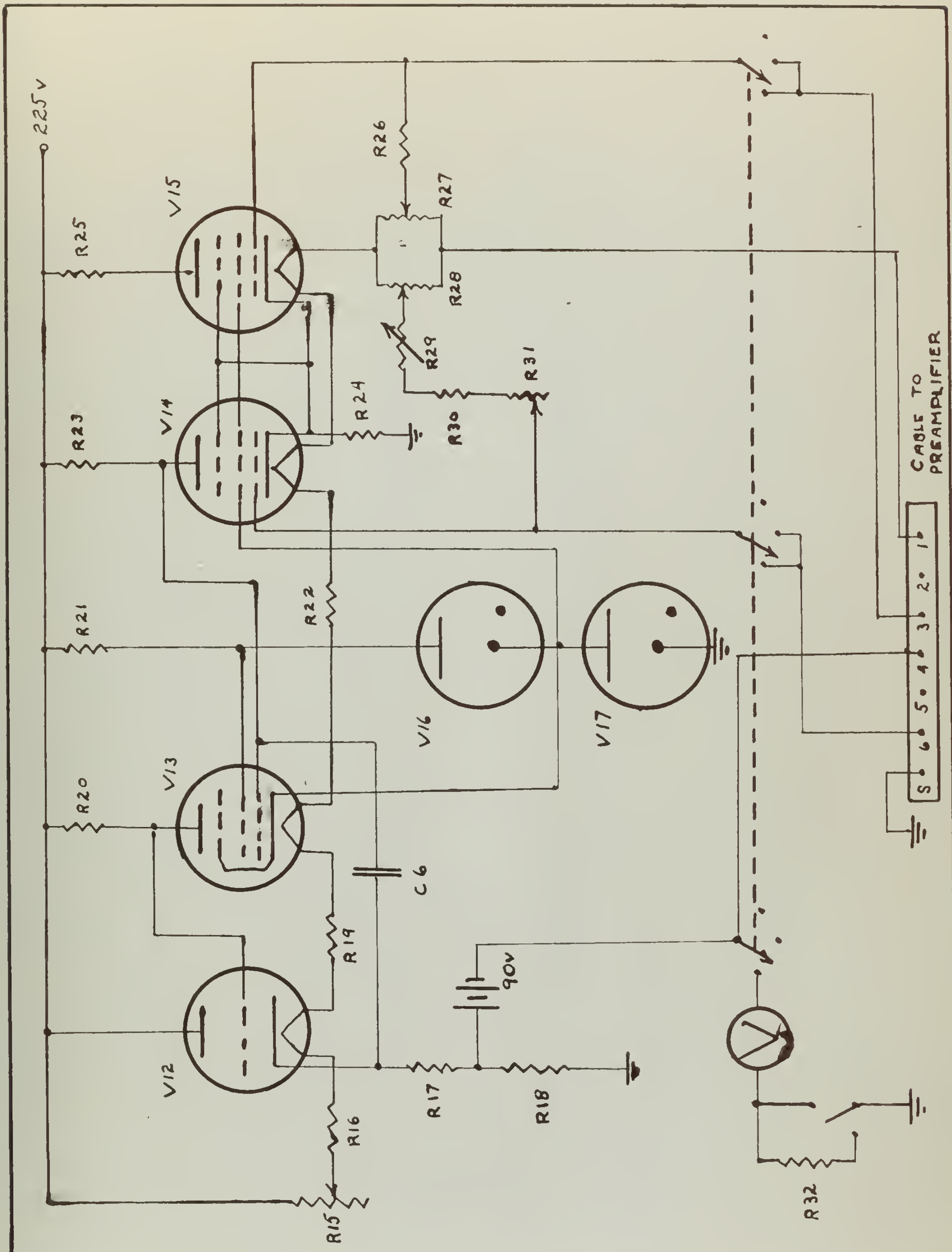


Fig 3b : Amplifier Circuit Diagram

Figure 3d

Values of Circuit Elements

Element	Value	Element	Value
V- 1	5 Y 3	R- 1	5 K
2	5 U 4	2	1 M
3	VR-150	3	1 M
4	VR-150	4	50 K
5	807	5	50 K
6	807	6	3.9 K
7	6 J 5	7	100 K
8	991 neon	8	12.5 K
9	VR-75	9	1 M
10	6 SJ 7	10	1 M
11	6 SJ 7	11	100 K
12	12 J 5	12	25 K
13	12 SJ 7	13	1 M
14	12 SJ 7	14	20 K
15	12 SJ 7	15	500
16	VR-75	16	500
17	VR-75	17	10 K
18	VX-41-A	18	15 K
		19	100
		20	1 M
		21	7.5 K
		22	200
		23	1 M
		24	25 K
		25	1 M
		26	20 K
		27	200
		28	200
		29	20 K
		30	200 K
		31	200 K
		32	100 K
		33	1×10^{12}
		34	5 K
		35	15
		36	25

Ionization Chamber:

The ionization chamber used as a means of studying the intensity distribution of the beta ray field is shown in Figure 4. It is supported from a plastic disc in the preamplifier housing, and is directly connected into the preamplifier. The chamber has a volume of 0.008 ml. Since 1 r/sec is the equivalent of 2.08 x 10^9 ion pairs/sec/ml, or one statcoulomb/sec/ml, 1 r for this chamber volume is 7.416 x 10^{-15} amperes. This would give a signal input to the grid of the preamplifier of 7.416 mv/r/sec, and if one were to use a source of 100 r/sec, the grid swing of 0.7 volts would still be within that allowable for the VX-41-A used.

Various window materials were tried with this chamber, and the chamber was also tried as an open-ended chamber. This latter proved to be unsatisfactory since water vapor from the surface of the phantom shorted the chamber. The most satisfactory window material used was 0.002 inch Zapon. Plastics such as Zapon are so close to the stopping power of water and are so thin that they need not be taken into account in computing the reduction in beam intensity by passage through the water phantom. Aluminum windows were tried and found to be unsatisfactory. Electrolytic action in the phantom tank rapidly produced pin-holes in the window, which resulted in the short-circuiting of the chamber. This effect was partially eliminated by placing the entire bath at the same potential as the window, but enough

Ionization Chamber

The ionization chamber used as a means of studying the intensity distribution of the beta ray field is shown in Figure 4. It is supported from a plastic ring in the preamplifier housing, and is directly connected into the preamplifier. The chamber has a volume of 0.008 ml. Since 1 r/sec is the equivalent of 2.08×10^9 ion pairs/sec/ml, or one electrostatic unit/sec/ml, 1 r for this chamber volume is 7.410×10^{-13} amperes. This would give a signal input to the grid of the preamplifier of 7.416 mv/sec, and if one were to use a range of 100 r/sec, the grid swing of 0.7 volts would still be within that allowable for the [illegible] used.

Various window materials were tried with this chamber, and the chamber was also tried as an open-ended chamber. This latter proved to be unsatisfactory since water vapor from the surface of the phantom shorted the chamber. The most satisfactory window material used was 0.00[illegible] inch nylon. Plastics such as nylon are so close to the atomic number of water and are so thin that they need not be taken into account in computing the reduction in beam intensity by passage through the window material. Aluminum windows were tried and found to be unsatisfactory. Electrolytic action in the phantom bath rapidly produced pin-holes in the window which resulted in the short-circuiting of the chamber. This effect was partially eliminated by placing the entire bath at the same potential as the window, but enough

ION CHAMBER

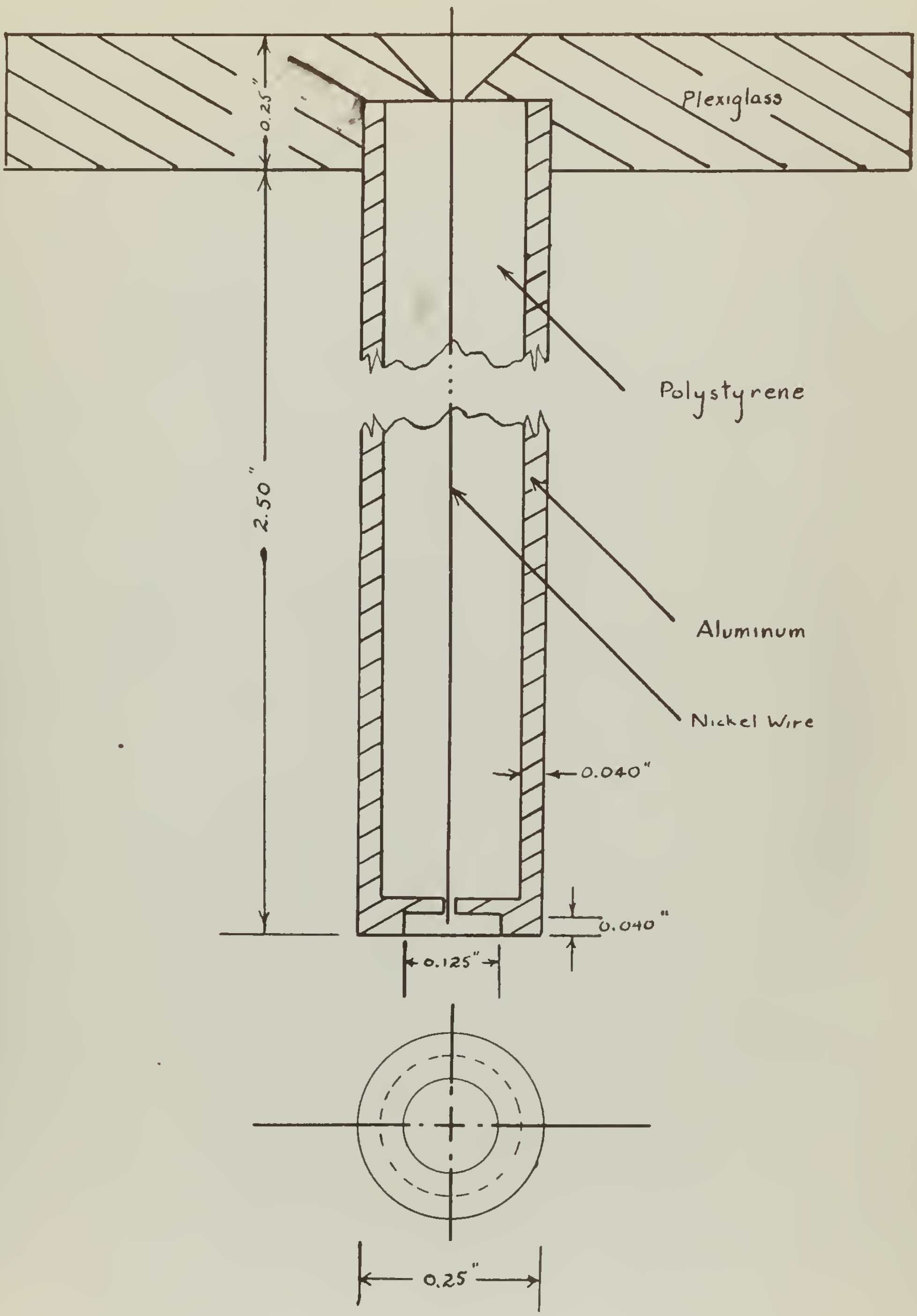


Fig 4

aluminum continued to enter into solution, although much more slowly, to produce punctures in the foil.

Applicator Holder:

The applicator holder used in these tests (Figure 5) was designed to take advantage of the low atomic number of aluminum in the production of X-radiation. The actual structural design was as shown to permit easy and rapid changes from one source to another, as well as to permit the taking of data on one type of beam collimator (the source may be placed in position at either end of the retaining cylinder).

The beryllium-base source may also be used in this holder for comparison purposes, although such a massive construction would not be used in therapy.

Tissue Phantom:

To determine the penetration pattern of the Rh 106 beta particles in tissue, it was necessary to devise some method of simulating the stopping power of soft tissue, since the use of tissue itself is not practicable. Water is commonly used for that purpose(15,16,30,36), and was used here.

In this system, there also had to be included provisions for accurately varying the position relationship between the emitting surface and the measuring device (ion chamber), provision for measuring these variations, and safety measures for protecting

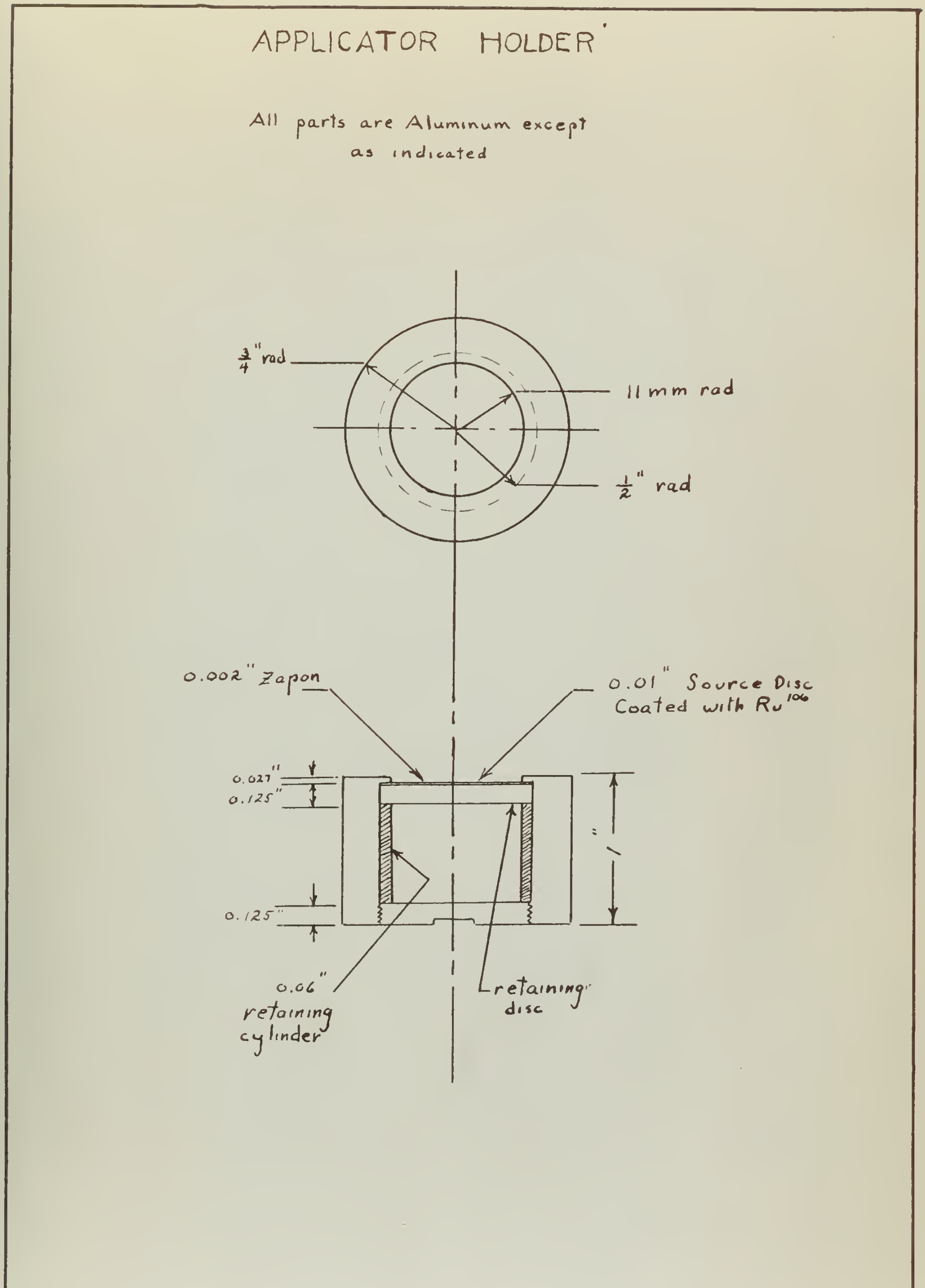

APPLICATOR HOLDER
All parts are Aluminum except
as indicated
$\frac{3}{4}$" rad
11 mm rad
$\frac{1}{2}$" rad
0.002" Zapon
0.01" Source Disc
Coated with Ru^{106}
0.027"
0.125"
0.125"
1"
0.06"
retaining
cylinder
retaining
disc

Fig 5

the operator from the high beta flux involved.

The system as shown in Figure 6 was finally evolved after trial of several variations thereof. Since mechanical systems are vulnerable to the corrosive effects of water and electrolytes, frequently develop leaks, and contain inherent backlash and other mechanical difficulties, it was decided to employ a hydraulic system to drive the moving parts of this mechanism. The tank used was a glass cylinder, 9.56 cm inside diameter, and 10 cm long. This was mounted on a half-inch Plexiglas sheet drilled as shown, and fitted with glass nipples for attachment of the mercury reservoir and a bottom drain for removing mercury without removing water or otherwise disturbing the system. A Plexiglas stage was used upon which the applicator was mounted This whole assembly, plus the phantom water, was then floated on the mercury surface. The scale on the side of the tank is divided into millimeters, and can, therefore, be read to the nearest 0.1 mm with the aid of a suitable magnifying lens. Thus, by adding or substracting mercury from the system and reading the position of the Plexiglas stage, it is possible to determine the position of the source relative to the ion chamber. If greater accuracy or more finely spaced readings are desirable, it is merely necessary to compute from the physical dimensions of the tank the volume of mercury which must be added or taken away to provide the desired variation in source-chamber spacing. When employing the volumetric addition of mercury, constant temperature must

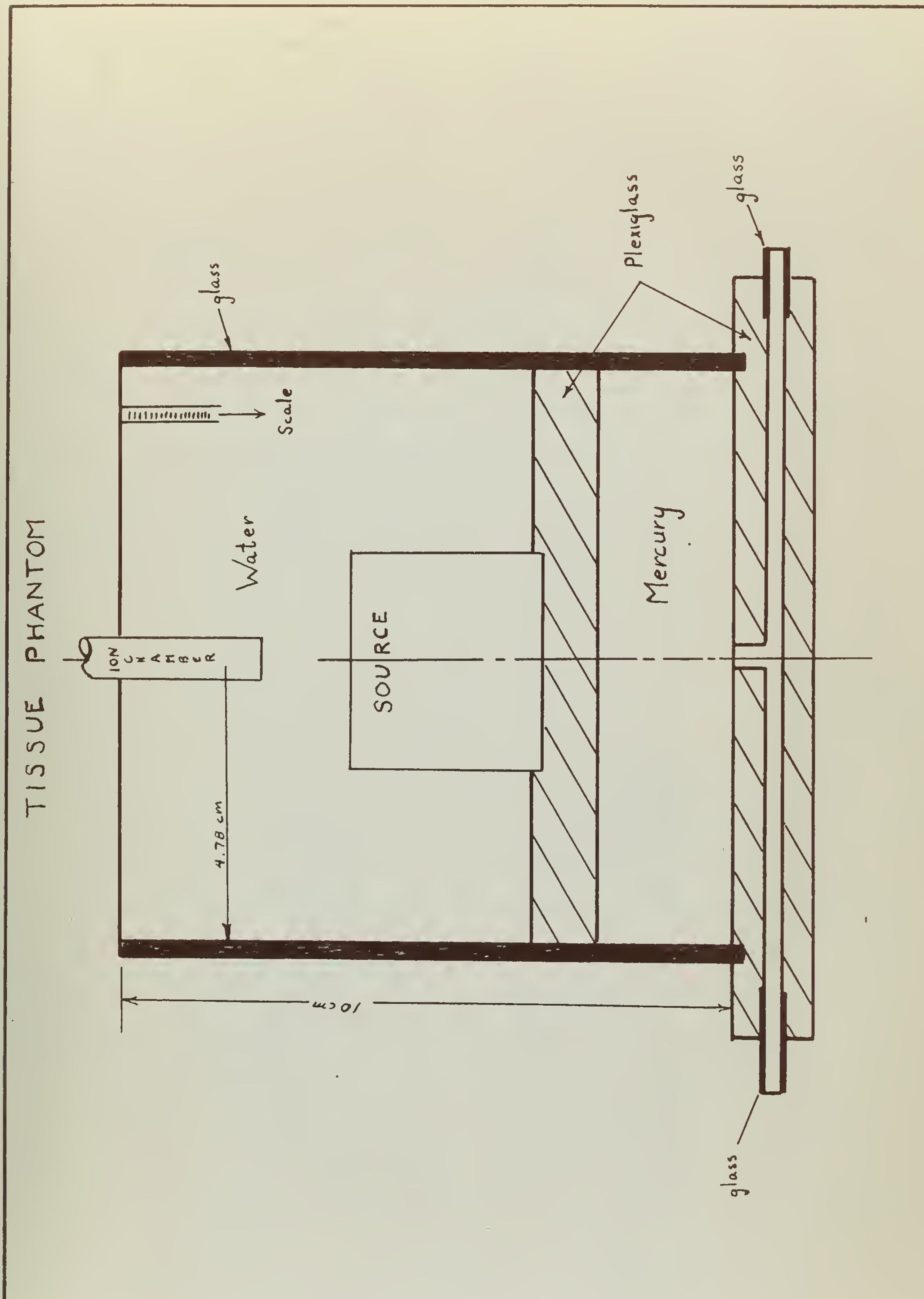

TISSUE PHANTOM
glass
Scale
Water
ION CHAMBER
SOURCE
Plexiglass
Mercury
glass
4.78 cm
10 cm
glass

Fig 6

be maintained to prevent expansion errors. For accuracy requirements within the limits of the tank scale, mercury is introduced from a separatory funnel as a convenient reservoir. Where greater accuracy requirements necessitate the volumetric addition of mercury, a burette is substituted for the funnel. Persons who may employ this system are cautioned that the burette must have a long stopcock, since a short stopcock will be forced out by the pressure of the mercury column in the burette. It is also suggested that all hose connections be clamped and lacquered to prevent spilling mercury. A traversing device for the ion chamber was also provided to facilitate reproducible readings at all points of the applicator surface. A siphon arrangement (not shown) was also provided for convenience in removing water from the tank during operation without exposing the operator to the radiation field. A light was mounted behind the tank to improve visibility. To add contrast between the Plexiglas stage and the water, a blue dye was added to the water. This greatly facilitated measurement and reduced eyestrain.

Incidental Equipment:

Other equipment used for gamma-ray readings, autoradiographs, and the adjustment of the electronic system were of the variety standard in any physics laboratory and merit no special mention or description here.

Procedure

Beta Ray Penetration Pattern in Water Phantom:

The equipment for this portion of the study was arranged as described. The actual measurement procedure, occasionally modified slightly for special variations, was as follows:

a. Preparation:

1. Balance and zero-set the metering system. This was checked periodically during all runs to insure continued satisfactory operation.

2. Introduce sufficient mercury into the tank to raise the source to a convenient level for the test to be performed. Immerse the ion chamber until contact is made with the surface of the applicator.

b. Measurement:

1. With the chamber in contact with the applicator, record the meter reading. This initial reading is normally made at the center of the applicator and is used as the "100% of Surface Dose" reference. Record, also, the position of the stage.

2. Move the ion chamber to other points on the surface of the applicator and record the meter reading and position data at each point. These lateral points at which readings are made are selected to provide data which will permit accurate determination of the penetration pattern.

3. Drain mercury from the tank until the desired source-chamber spacing is obtained. Record the new stage position and the meter readings at each of the lateral positions selected in Step 2.

4. Repeat Step 3 at as many positions as may be necessary to obtain sufficient data to plot a curve of intensity versus distance for each point on the applicator surface. The source-chamber spacing is determined as the difference between the contact position of the stage and the position at any given reading. Distance intervals of 0.2 or 0.3 mm were used up to ranges where the intensity became less than 70% of the surface intensity and where pattern fringes were being examined. This was done to locate the knee of the curve accurately (Figure 7). Greater intervals are permissible thereafter.

5. For each reading obtained in Steps 2-4, compute the percentage of the contact reading, using as reference the reading obtained in Step 1. From these data, plot isodose patterns for each source employed (i.e., Figure 8).

Autoradiographs:

Autoradiographs were introduced into this study to provide the reader with visual conformation of some of the information determined during the penetration measurements in the tissue phantom.

As was mentioned previously, the nonuniformity of source plating is demonstrated by Figures 1 and 2. Additional autoradiographs were prepared to substantiate the isodose patterns obtained by electronic measurement. These are included in the data section, along with photodensitometer readings obtained therefrom. These were prepared by stacking film to a depth equivalent to the maximum range of the beta particles and applying the source to the top of that stack for the indicated period, or by mounting the film vertically between paraffin blocks and applying the source to the edge of the film. Each film layer with emulsion was measured to have an average thickness of 0.223 mm and a density of 1.41 gm/cc. Thus, each 0.71 mm of film has an equivalent stopping power of 1 mm of tissue or water. Figure 7 demonstrates the correlation between the densitometric data and the electronic data along the axis of the applicator. Since film emulsions undergo a saturation effect at high intensities[40], proper correlation at close ranges is difficult to accomplish.

Exposures are indicated with each autoradiograph. Du Pont Type 508 X-ray film was used, and was developed according to the manufacturer's specifications (4 minutes in Du Pont X-ray Developer; 10 minutes in Kodak X-ray Fixer; 68 degrees F.).

<u>Biological Effects</u>:

The information obtained in the brief biological test done in conjunction with this study cannot be considered adequate.

The test was merely performed to obtain an indication of the nature of the biological reaction to a Ru 106 source.

Source 2 was taped to the shaved back of a male rabbit for a period of 15 hours and 40 minutes, for a total surface dose of 23,900 rep. The rabbit was then observed periodically to determine any biological effects.

Data and Computations

Preparation of a Therapeutic Applicator:

To prepare a therapeutic applicator which will provide a dose rate suitable for clinical use, the physician's requirements must be considered. Each tumor type possesses its own minimum lethal dose which must be applied to [illegible]nsure growth [6,17,2[illegible]

condition of the [illegible]

periods of treatment. In addition, evidence has been presented which purports to show a relationship between the effectiveness of the total dose and the rate at which it is applied[6]. It is the function of the physician to correlate these factors and select the optimum total dose and optimum dose rate for a particular pathological condition. This paper does not attempt to do this for him.

Included herein are the calculations to be used to determine the activity for a specific treatment based upon [illegible]

the desired total dose and the rate at which it is to be administered.

Rh 106 has two decay paths for each of which separate calculation must be made to determine the actual energy transferred to an irradiated area.

Assuming no Bremsstrahlung to be present (introduced later), the rate at which energy is emitted from any beta source is:

energy/sec = (number of beta particles emitted/sec) (average energy per particle).

<u>Eq 1</u> ergs/sec = $kN\bar{E}M$ where M = number of mC present

N = number of particles emitted per mC

$= 3.7 \times 10^7$

k = conversion factor from Mev to ergs

$= 1.6 \times 10^{-6}$ ergs/Mev

$\bar{E}$ = average energy per particle (Mev)

To obtain the dose rate in any medium in rep/sec, one must use the rep as defined: 1 rep = 95 ergs absorbed per gram of absorbent tissue. The mass of absorbent in any material is:

<u>Eq 2</u> gms = dAR where d = density

A = area of surface irradiated

R = range of particle of average energy $\bar{E}$

Division of Eq 1 by Eq 2 then gives the dose rate of the source material as:

Eq 3 rep/sec/gm of tissue = $k N \bar{E} M q / d A R$ where q = conversion factor from ergs to rep as defined above = 1/95

Using the density of tissue as unity and assuming, temporarily, 100% geometry, substitution of the appropriate conversion factors into Eq 3 gives:

$$\text{rep/sec} = \frac{(3.7 \times 10^{7})(1.6 \times 10^{-6})}{95} \cdot \frac{M\bar{E}}{AR}$$

$$= 0.623 \, \frac{M\bar{E}}{AR}$$

Eq 4

Application of Eq 4 to a Sr 90 applicator produced and calibrated by Tracerlab, Inc., gives values comparable to those obtained by the calibration measurements, within a suitable geometric correction. This applicator contains approximately 25 mC of Sr 90, maximum beta energy of 2.2 Mev, and was measured by the manufacturer to provide 28.1 rep/sec at the surface.

The following equation(27) permits calculation of the average energy per beta particle:

Eq 5 $$n = \bar{E}/E_{max} = 0.33\left(1 - \frac{Z}{43}^{1/2}\right)\left(1 - \frac{E_m}{4}^{1/2}\right)$$

where n = the ratio of the average beta particle energy to the maximum beta particle energy.

For Sr 90, the average energy is therefore:

$$\bar{E} = n\,E_m = (2.2)(0.33)\left(1 - \frac{38}{43}^{1/2}\right)\left(1 - \frac{2.2}{4}^{1/2}\right)$$

$$= 0.853 \text{ Mev}$$

Employing this average energy in Eq 4, the Sr 90 applicator in question having a diameter of 7.7 mm, the dose ratio is:

$$\text{rep/sec} = \frac{0.623\ (0.853)(25)}{0.330\ (\frac{\Pi}{4}\ 7.7^2\ )} = 86.5 \text{ rep/sec}$$

To obtain the calibrated value of 28.1 rep/sec, an adjustment factor of 32.5% must be applied to account for losses due to applicator geometry and to account for conversion of beta particle energy to Bremsstrahlung. This correction would seem to be of the proper magnitude based on the limited available information on the internal construction of this Sr 90 applicator, and allowing for the approximation error in the 25 mC value.

Similar calculations for Rh 106 show the average energies of the two beta particles to be:

$$\bar{E} = 1.45 \text{ Mev} \quad \text{for } E_m = 3.55 \text{ Mev}$$

$$\bar{E} = 0.88 \text{ Mev} \quad \text{for } E_m = 2.30 \text{ Mev}$$

Application of these average energies to Eq 4, with proper allowance for the 82%-18% relationship between the two decay paths, and using unit area for the source, shows:

$$\text{rep/sec} = \frac{0.623}{A} \left(\frac{g\bar{E}}{R}\right)_1 + \frac{0.623}{A} \left(\frac{g\bar{E}}{R}\right)_2 \quad \text{for 1 mC}$$

where subscript 1 pertains to the 82% decay path, and

2 pertains to the 18% decay path

g = fraction of transitions by the selected path

The range (cm of tissue) for the 1.45 Mev particle is 0.645 cm, and for the 0.88 Mev particle is 0.344 cm.

Substitution of the given values of g, $\bar{E}$, and R, and assuming unit area for convenience, gives:

$$\text{rep/sec} = \frac{0.623(1.45)(0.82)}{0.645} + \frac{0.623(0.88)(0.18)}{0.344}$$

$$= 1.429 \text{ for 1 mC Rh 106 on 1 sq cm of surface}$$

The test applicator employed herein has a geometry factor of approximately 50% when reflection from the plating base and radiative losses are taken into account. Thus, for each mC/cm^2 exposed in this system, 0.715 rep/sec enter the area to be irradiated. This is not true in the present practice, since the nonuniformity of the plated surface has already been demonstrated, and the inaccuracies of the ORNL shipping data have been mentioned. Assume 3 mC to be plated uniformly on a Cu disc 1 inch in diameter. Since a 1/8 inch lip covers a portion of the emitting surface, only 56.3% of the emitter is exposed, leaving 1.69 mC effective in creating the beta field. Applying the geometric corrections, this applicator has 0.593 mC/cm^2, and therefore, supplies (0.593)(0.715) = 0.424 $rep/sec/cm^2$ to the irradiated surface.

In the preparation of a practical therapeutic applicator, it is desirable that a minimum of the active emitter be masked by the supporting structure. This can be accomplished by reduction of the width of the supporting lip and/or by masking the area, which is to be covered by the supporting structure, such that no active deposit is made in this region during electroplating.

In the preceding discussion, the production of Bremsstrahlung was omitted in order not to detract from the discussion at that time. Since this process accounts for an appreciable

portion of the electromagnetic radiation in a problem of this sort, and, therefore, is a major contribution to the radiation hazard of high energy beta ray sources, it must be taken into consideration.

In the introductory remarks, it was noted that the true efficiency of conversion of electron energy to X-radiation is probably not an exact linear function of the atomic number. However, since such a true relationship is not yet available, the direct proportionality approach will be employed for the purposes of this discussion. The following equation(29) will be used:

Eq 6 $n = bE\ Z/1600\ mc^2$ where:

n = the portion of the energy converted to Bremsstrahlung

bE = the average energy for a given beta ray spectrum

mc^2 = the rest mass of the electron = 0.00055 mu = 0.512 Mev

Consider only the active disc without any applicator holder, such that the Bremsstrahlung emission is due almost entirely to electrons impinging on the plating base. Over all of the beta energies from Rh 106, the average is 1.35 Mev; therefore, this case, $n = 1.65 \times 10^{-3}Z$. Values of n for the materials in this project are included in the table:

TABLE 1

Plating Base	n	Range $E_{av} = 1.35$	Range $E_m = 3.55$
Gold	0.130	0.31 mm	0.99 mm
Copper	0.048	0.67 mm	2.15 mm
Aluminum	0.021	2.21 mm	7.13 mm
Beryllium	0.006	3.29 mm	11.10 mm

From the above values of n, it is readily seen that beryllium is by far the best plating base for use in attempting to reduce the X-radiation field around a beta applicator. It is unfortunate that the sources did not arrive from ORNL in sufficient time, or with sufficient accompanying information, to permit verification of this statement with adequate experimental evidence.

This system contains a gamma-ray source. Allowances must, therefore, be made for this electromagnetic radiation as well as for Bremsstrahlung. As pointed out in the introductory material, the patient undergoing treatment is exposed only for the period of the treatment, and need not be considered in the long-term radiation-exposure picture. Therefore, in computing the gamma-ray intensity about one of these sources, dose rates will be figured as pertaining to the physician, who, in general, will be in close proximity to the patient only while actually fastening an applicator to the patient's person. Since he will be some distance away (at least arm's length) for the remainder of the treatment, the

TABLE I

Plating Base	R	Range (E max = 1.33)	Range (Ee = 1.45)
Gold	0.130	0.31 mm	0.99 mm
Copper	0.049	0.67 mm	2.15 mm
Aluminum	0.022	2.22 mm	7.23 mm
Beryllium	0.026	3.27 mm	11.10 mm

From the above values of R, it is readily seen that beryllium is by far the best plating base for use in minimizing to reduce the B-radiation field around a beta applicator. It is unfortunate that the source did not arrive from ORNL in sufficient time, or with sufficient accompanying information, to permit verification of this statement with adequate experimental evidence.

This system contains a gamma-ray source. Allowance must, therefore, be made for this electromagnetic radiation as well as for Bremsstrahlung. As pointed out in the introductory material, the patient undergoing treatment is exposed only for the period of the treatment, and need not be considered in the long-term radiation-exposure picture. Therefore, in computing the gamma-ray intensity about one of these sources, dose rates will be figured as pertaining to the physician, who, in general, will be in close proximity to the patient only while actually fastening an applicator to the patient's person. Since he will be some distance away (at least arm's length) for the remainder of the treatment, the applicator may be considered to function as a point source. Computations may, therefore, be made by the use of the following equation[28]:

<u>Eq 7</u> $$R/hr/mC = \frac{\sigma\,(E/photon)(photons/sec)(sec/hr)}{(ev/ion\ pair)(ion\ pair/R/cc)(4\Pi r^2)}$$

Computing the dose rate at one meter from a Ru-Rh source, one must take into account the three different gamma-ray energies involved. Eq 7 then becomes:

$$R/hr/mC \text{ at } 1\text{ m} = \frac{(3.6\times10^{-5})(3.7\times10^{7})(3600)10^{6}}{(32.5)(2.08\times10^{9})(4\ \Pi\ 10^{4})}\,(\varepsilon_1E_1 + \varepsilon_2E_2 + \varepsilon_3E_3)$$

$$= 0.127 \times 10^{-3}$$

where, ε_1 = fraction of transitions by a given path
E_1 = energy of the emitted photon by the given path
$\varepsilon_1E_1 + \varepsilon_2E_2 + \varepsilon_3E_3 = 0.17 \times 0.51 + 0.17 \times 0.73 + 0.01 \times 1.25$

<u>Beta Ray Penetration Pattern in Tissue Phantom:</u>

The data obtained by measuring depth dose as a function of surface dose are presented in Figures 7, 8, and 9.

Figure 7 includes the axial depth-dose data obtained from Source 2 (in the Al holder) by ion chamber measurement, a curve for a Sr 90 applicator[16] for comparison purposes, and photodensitometric readings from the autoradiographs (Figure 11). It may be seen that the Sr 90 applicator field falls to 50% of its surface intensity at 0.8 mm penetration into a water phantom, at which distance the intensity of the Ru 106 applicator field remains in excess of 100%. Theoretical concepts indicate that a

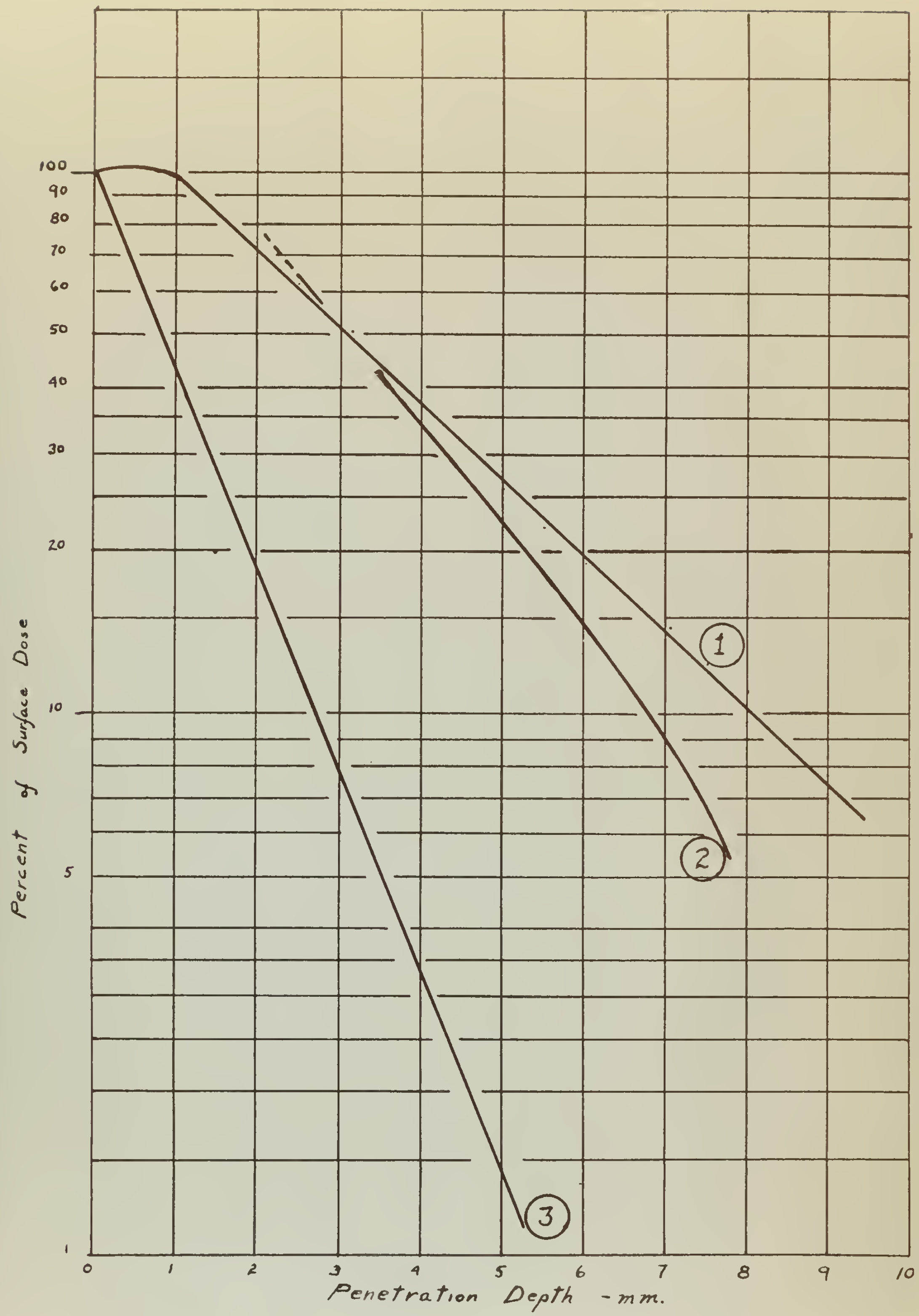


FIG 7 : Depth Dose Curves in Water Phantom
① Ru^{106} Test Applicator (ION CHAMBER)
② Photodensitometric Data on Ru^{106} Applicator
③ Sr^{90} Applicator

similar plateau should appear for the Sr 90 applicator. However, in medical practice, it is necessary to filter the 0.63 Mev particle emitted by the Sr 90 since it will produce an undesirable necrotic condition at the tissue surface while the therapeutically effective 2.2 Mev particle from Y 90 is delivering the desired depth dose. This condition does not exist in the Ru-Rh system, since the Ru 106 particle is of such low energy. It is also notable that at a depth of 5 mm, the Sr 90 dose rate is less than 2% of the surface dose while that from Ru 106-Rh 106 sources is still 26% of the surface rate. Thus, it may be seen that the use of Sr 90 applicators entails thirteen times the total surface dose of a Ru 106-Rh 106 applicator to produce the same dose at 5 mm depth, with a proportionately more severe surface necrosis.

The family of curves in Figure 8 represents the gradation of depth dose as measurements are made laterally across the face of the test applicator. The axial contact reading is used as the 100% reference. The beta ray beam appears to be quite well collimated by the 0.7-mm aluminum lip of the container structure, since the intensity beyond the limits of the exposed emitting surface does not exceed a small fraction of the intensity of that portion of the field to be used in therapy. However, for long exposures, additional collimation may be desirable as evidenced by the autoradiographs shown in Figure 12. This requirement would, of course, be adjusted to the type of tumor growth or other lesion to be irradiated, since

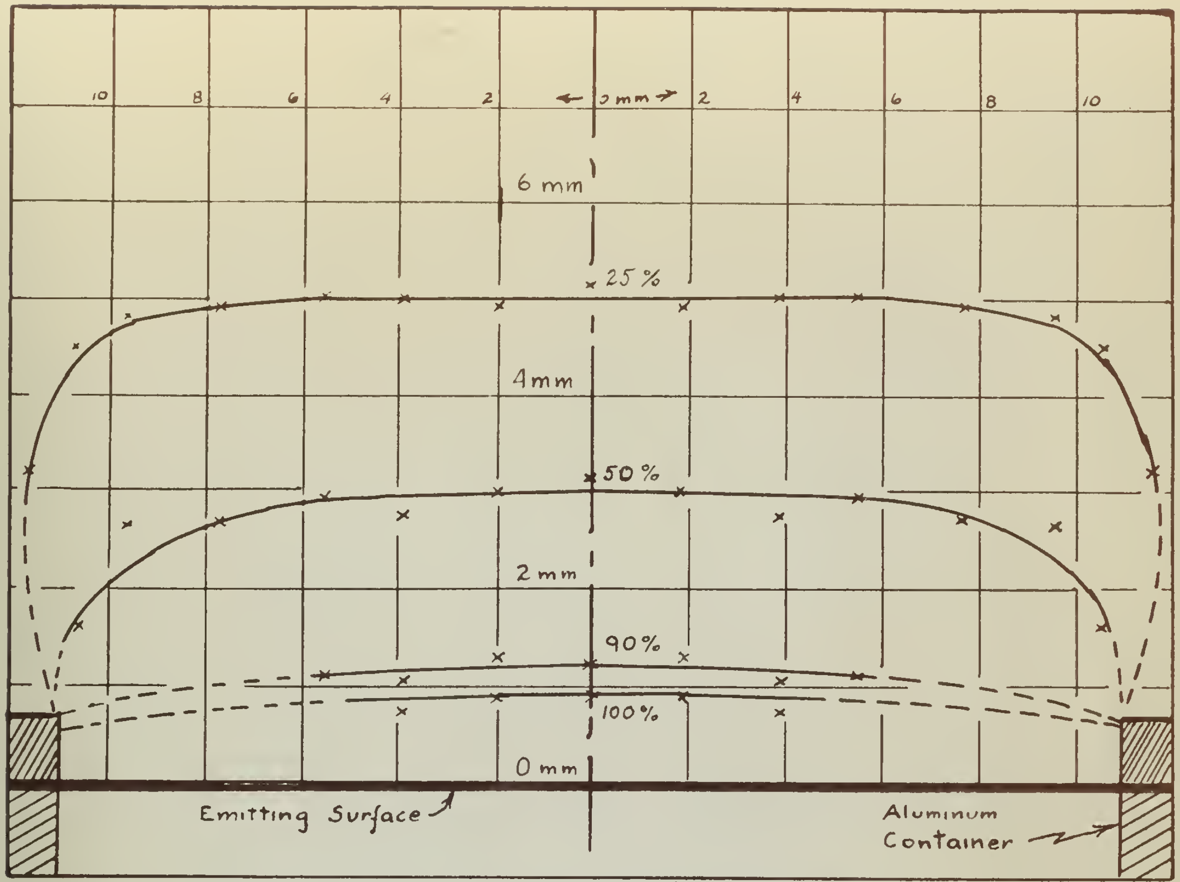


Fig 8: Isodose Curves around Ru^{106} Applicator Immersed in Water

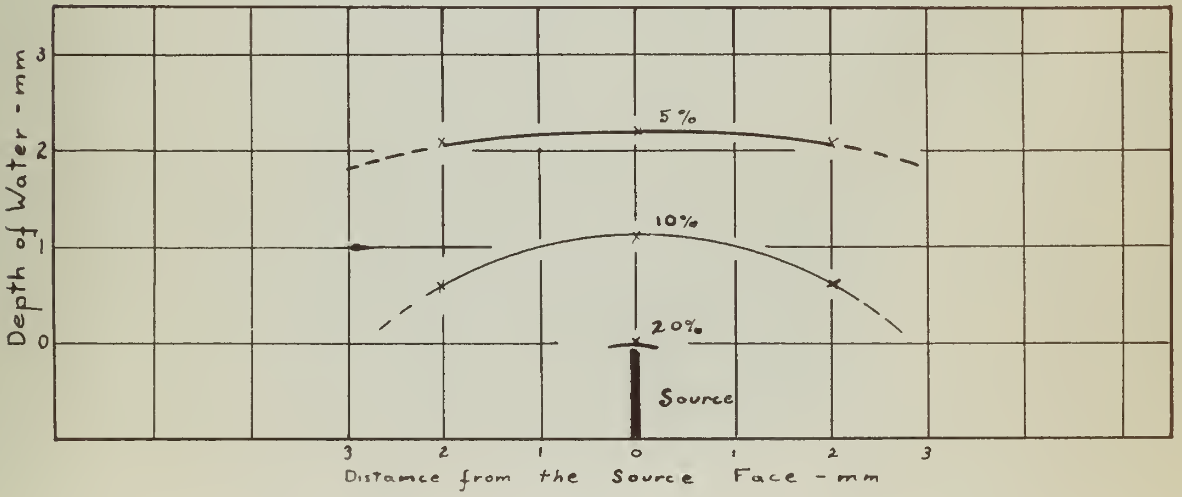


Fig 9: Isodose Pattern at the Edge of Source 2 Immersed in Water. Percentages are of the axial contact reading

some cases may require a rather high total dose at all the fringes and on into the surrounding skin. In measuring these isodose patterns, readings were taken along a single radius line in order to present the conditions which would prevail if the source had been properly plated. The curves shown are for a completely immersed source. Tissue may not fill the recess in the applicator face in actual practice. The isodose pattern could then be applied from the tissue surface rather than the emitting surface, and would, therefore, give a better collimating effect. Due to the physical dimensions of the ion chamber and applicator (Figures 4 and 5), it was not possible to complete a closed traverse of the 100% and 90% isodose curves in the region of the retaining lip of the applicator. No intensity in excess of 25% of the surface dose rate was noted on the surface of the applicator at a radius of 13 mm from the center, and no beta intensity was measureable at the edge, back, or side of the container. Combined gamma ray and Bremsstrahlung readings, using a Geiger-Mueller counter, (no beta) for Source 2 showed 14 mr/hr after penetration of 4 cm of tissue equivalent plastic.

Figure 9 is an isodose plot of data obtained using the ion chamber and approaching the edge of the unshielded Source 2 (no container) immersed in water. It is indicative of the relatively small amount of collimating material necessary to confine the beta particle beam to the desired limits. Even as the ion

chamber approached so close to the edge of the disc that appreciable radiation could enter directly from either face of the disc, the intensity did not exceed 20% of the axial reading. Since the geometry was so unsatisfactory in the measurements involved here, it is safe to say that the true gradient and maximum value is much more favorable than indicated.

Autoradiographs:

The autoradiographs shown in Figures 10, 11, and 12 were prepared in confirmation of the information obtained by electronic measurement.

Figure 10 was obtained by laying the applicator holder, with Source 2 in place, on its side on a strip of X-ray film. It serves to demonstrate that no particulate emission is observed from the sides of the container. The apparent curvature of the edge is due to the geometry of a circular source standing on edge on a flat plate. The apparent fringing is also due to this geometrical distortion.

Figure 10. Applicator placed on its side on X-ray film to demonstrate sharp cutoff of radiation field at applicator surface. Exposure = 5 sec. Source 2.

chamber positioned so close to the edge of the film that appreciable radiation would occur directly from either face of the film, the intensity did not exceed 10% of the usual reading. Since the geometry was so unsatisfactory in the measurements involved here, it is safe to say that the true gradient and maximum value is much more favorable than indicated.

__Autoradiographs:__

The autoradiographs shown in figures 10, 11, and 12 were prepared in confirmation of the information obtained by electronic measurement.

Figure 10 was obtained by laying the applicator holder, with Source 5 in place, on its side on a strip of x-ray film. It serves to demonstrate that no particulate emission is observed from the sides of the container. The apparent curvature of the edge is due to the geometry of a circular source standing on edge on a flat plate. The apparent fringing is also due to this geometrical distortion.

__Figure 10.__ Applicator placed on its side on X-ray film to demonstrate sharp cutoff of radiation field at applicator surface. Exposure = 3 hrs. Source 5.

__Figure 11.__ This is a portion of a series of autoradiographs obtained by stacking X-ray film in front of the applicator. It demonstrates the variation in depth dose: Exposure = 1 sec. Source 2.

a. Contact

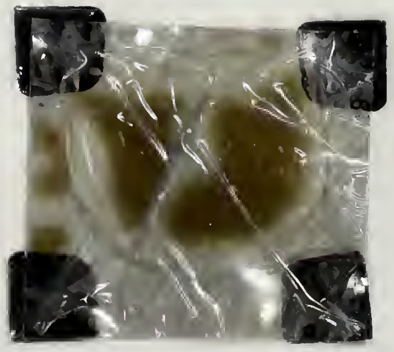
b. 5 layers of film
0.156 gm/sq cm

c. 10 layers of film
0.312 gm/sq cm

d. 15 layers of film
0.468 gm/sq cm

Figure 11. (continued)

e. 20 layers of film
0.624 gm/sq cm



f. 25 layers of film
0.780 gm/sq cm

g. 30 layers of film
0.936 gm/sq cm

Figure 12. Edge of X-ray film exposed to beta-ray field from applicator. Demonstrates the outline of the radiation field. Exposures = 5 and 20 sec. Source 2.

Figure 11 is a portion of the series of autoradiographs obtained by stacking X-ray film and permitting the beta ray beam from Source 2 (in holder) to penetrate through the pile. Densitometric data are shown in Figure 7. The contact exposure shows the rather slight fringing at the edge of the applicator which can be greatly reduced by additional collimation.

Figure 12 is an edge exposure and is, in effect, a photographic reproduction of Figure 8. This was greatly overexposed in order to demonstrate the outline of the entire beta field.

Biological Observations:

The observations included here are presented in diary form for convenience of interpretation. Elapsed time is computed from the time at which the applicator, containing Source 2, was mounted on the test animal.

Date and Time of Observation	Elapsed time Hrs:Min	Observations and Comments
1540, 25 April		Applied source to the shaved nape of rabbit's neck with adhesive tape. No breaks in the skin were observable.
0720, 26 April	15:40	No observable effect at removal of applicator.
1600, 27 April	48:20	Definite erythema existed over an area the size and shape of a kidney bean, corresponding to the more active portion of the applicator (see Fig. 2). The coloration was about that of a moderately severe sunburn.

0815, 28 April	64:35	Complete erythema existed over an area 22 mm in diameter. The entire area was of the same color previously observed, except that the area noted 27 April had become a deep magenta and portions thereof had become necrotic. There was no discoloration observable outside an area equivalent to the exposed emitting material of the applicator.
0815, 30 April	112:35	Severe necrosis was evident over the entire area, with some sloughing in the area corresponding to the more densely plated portion of the source.
1245, 1 May	141:05	The necrotic area appeared generally the same, with the addition of two open lesions approximately 1 mm in diameter, which were present in the most intensely irradiated area. A mild erythema had appeared in a band about 1 mm wide surrounding the necrotic area, apparently due to the low intensity fringing noted in Figure 8.
1300, 3 May	189:20	The entire area appeared the same as on 1 May, with some additional loss of skin near the edges of the necrotic area, and in the spots previously noted.
1300, 5 May	213:20	No apparent change.
0900, 12 May	377:20	No further sloughing of skin was observed. The necrotic area was the same size. The erythematous area noted on 1 May appeared to have returned to normal. The hair surrounding the necrotic area had grown 1/8 to 1/4 inch. There was no apparent hair growth in the injured area, nor was there any observable epillation.

At all times during these observations, the animal appeared to be otherwise completely normal.

From the observation of this test animal, it is apparent that any radiation damage to tissue subjected to irradiation by a

Ru-Rh applicator of this type is confined to the area immediately adjacent to the emitting surface, and that any fringing effects are of limited severity and heal rapidly.

No histological sections were studied in a limited test of this nature. They should, however, certainly be included in the extensive animal studies which must be done before this beta-ray applicator may receive any extensive clinical use.

CONCLUSIONS

Consideration of the isodose and penetration intensity curves for soft tissue, obtained in this study, shows a Ru 106, Rh 106 applicator to be very satisfactory for use in radiation therapy.

Properly collimated, the high-energy beta particles supplied by Rh 106 provide a strong radiation field to a depth of more than 5 mm. Use of this isotope does not entail heavy surface necrosis due to a low-energy beta particle from the parent Ru 106, nor does it require appreciable attentuation of the usable beam to filter out low-energy particles. Thus, for treatment of surface lesions to a depth of several millimeters, an adequate field can be established without the introduction of other pathological conditions. For treatment of superficial surface conditions, such as fungus infections, the 0.9-mm 100% dose-rate region permits high-intensity, surface irradiation without causing extensive damage to the underlying tissue.

Proper collimation of the beta-ray beam to suit the therapeutic problem can readily be obtained by variation of the mechanical structure of the applicator holder.

Although gamma radiation is inherent in the use of this isotope family, the intensity thereof is below established gamma-ray tolerance values for sources having beta-ray dose rates in the normal therapeutic range. The gamma-ray intensity from Rh 106 is much

lower than that from radium sources of the same beta-ray intensity. Dr. Neary(30) has compiled the ratio of the intensities of these two radiations for typical radium plaques and also the gradient of dose rate with depth. He has stated:

> "The value of the beta-gamma ratio for a full-strength applicator with surface dose-rate about 5,000 r/hr is of the order of 25" . . . . . .

and

> "The most striking feature is the very rapid fall-off of the depth dose; e.g., only about 50 per cent at 1 mm."

A similar computation for Ru 106 applicators, based on the values obtained herein (see Preparation of Applicator) shows:

$$\text{beta/gamma } \frac{0.715}{0.127 \times 10^{-3}} = \frac{\text{beta dose rate/mC}}{\text{gamma dose rate/mC}}$$

$$= 5.63 \times 10^3 \text{ for Ru 106, Rh 106.}$$

It is readily seen that, from the point of penetration of beta particles, Ru 106 is greatly superior to both radium and Sr 90 applicators as currently prepared, and has a beta-gamma ratio advantage over radium by a factor of 210. It is believed that the advantages of the Ru 106 beta-ray penetration pattern are so superior to those of Sr 90 that the low gamma-ray intensity which is introduced may be tolerated, especially in view of the intensity currently tolerated in the use of radium.

Ru 106 is also superior to radium in that no gas-leakage hazard exists.

Bremsstrahlung can be materially reduced by employment of plating bases and containers of low atomic number elements. Of the lower atomic number materials, beryllium is the most satisfactory in that it is a light, strong solid, and is not nearly so chemically active as some of its neighbors in the periodic table. Its toxic effects can be readily prevented by proper handling.

The half life of Ru 106 is long enough that an applicator constructed thereof has an output of sufficient constancy for normal therapeutic use. A simple decay curve based on its initial calibration value is adequate to determine the dose rate at the start of a treatment. Such a small portion of one half-life transpires during the few hours of a treatment period as to permit the assumption of constancy of output for the period in question.

Examination of the limited available biological data described indicates the true tissue effect to be as predicted by the measurements in the tissue phantom and by the autoradiographs.

SUMMARY

The problem of the depth-dosage distribution due to beta particle irradiation from sources of Ru 106 in equilibrium with Rh 106 is studied in terms of ionisation-chamber measurements in a tissue-equivalent, water phantom.

The equipment and methods employed are described in detail for the assistance of those who may do further studies of this sort.

Auxiliary data are provided by autoradiographic studies using the various sources available.

Calculations are shown to be in accord with the available experimental data on the sources studied. The results of the calculations and experimental data demonstrate Ru 106 applicators to be practicable sources of high-energy beta rays for use in radiation therapy. The electromagnetic radiation involved in its use is small and may be further minimized by use of structural materials of low atomic number. The fall off of beta-ray dose rate with tissue depth provides a region of 0.9-mm depth at 100% of the surface dose rate, and a logarithmic decline from 0.9 mm to 25% at 5 mm.

Examination of limited biological evidence confirmed the anticipated results as to area affected and depth of tissue reaction.

SUGGESTIONS FOR FURTHER STUDY

Ru 106 beta-ray sources have been shown to be physically acceptable for therapeutic use. Initial biological checks have confirmed the physical studies. Before this radioactive element may be placed in general clinical use, additional biological studies must be performed and analyzed, both as to the effectiveness of this type of applicator on normal tissue and on tumor tissue. In view of the failure of the beryllium-based source to arrive in time for study, this work must also be carried out. Additional design work must be done with respect to applicator shape and materials.

APPENDIX I

APPENDIX I

Bibliography

1. G. D. Adams, G. Almy, S. Dancoff, A. Hanson, D. Kerst, H. Koch, E. Lanzl, K. Lang, and J. Laughlin; Techniques for Application of the Betatron to Medical Therapy; Am. J. Roentgen. Rad. Ther. 60, 153-7 (Aug. 1948).

2. M. Blau and J. E. Smith; Beta-ray Measurements and Units; Nucleonics 2, No. 6, 67-74 (June 1948).

3. W. Blood; Histopathology of Irradiation from External and Internal Sources; McGraw-Hill (1942).

4. P. Brown; American Martyrs to Science Through X-ray; C. C. Thomas Co. (1936).

5. J. G. Burr and W. M. Garrison; The Effect of Radiation on the Physical Properties of Plastics; AECD-2078 (Dec. 1943).

6. S. Cade; Malignant Disease and Its Treatment by Radium; Williams and Wilkins Co. (1948).

7. W. E. Cohn; Toxicity of Inhaled or Ingested Radioactive Products; Nucleonics 3, No. 1, 21 (1948).

8. A. H. Compton and S. K. Allison; X-rays in Theory and Experiment; Van Nostrand (1949).

9. D. T. Eggen; A Study of Radioactivities in the Ruthenium Region; Ph. D. Thesis, O. S. U. (1948).

10. R. D. Evans; Radioactivity Units and Standards; Nucleonics 1, No. 2, 32 (Oct. 1948).

11. G. Failla, H. Rossi, R. Clark, and M. Baily; The Measurement of Tissue Dose of Ionizing Radiations; AECD-2142 (Dec. 1947).

12. E. Fermi; Nuclear Physics; Compiled by J. Orear, et al, University of Chicago Press (1950).

13. D. D. Ford; The Chemistry of Ruthenium; NP-1104, University of Kansas (1950).

14. H. F. Freundlich; A New Beta-ray Applicator Using Fission Products; Nature 164, 308-10 (Aug. 1949).

15. H. L. Friedell, C. I. Thomas, and J. S. Drohmer; Beta Ray Application to the Eye with Description of an Applicator Utilizing Strontium-90; Am. J. Opthalmology 33, 525 (1950).

16. H. L. Friedell, C. I. Thomas, and J. S. Krohmer; Description of a Sr 90 Applicator and Its Use on the Eye; Am. J. Roentgen. Rad. Therapy 65, 232 (Feb. 1951).

17. O. Glasser, ed.; Medical Physics, Vol. I; Year Book Publishers (1949).

18. L. E. Glendennin; Determination of the Energy of Beta Particles and Photons by Absorption; Nucleonics 2, No. 1, 12 (Jan. 1948).

19. A. M. Haik; Beta Irradiation as a Possible Therapeutic Agent in Glaucoma; Am. J. Opthalmology 31, 945-52 (Oct. 1949).

20. J. G. Hamilton; Metabolism of Radio-Strontium and Radio-Cerium; MDDC-1000, U. S. A. E. C.

21. G. W. Holmes and M. D. Schulz; Therapeutic Radiology; Lea and Febiger Co., (1950).

22. F. Hodges, J. Holt, I. Lampe, and R. MacIntyre; Yearbook of Radiology; Year Book Publishers (1950).

23. J. H. Lawrence and J. G. Hamilton; Advances in Biological and Medical Physics; Academic Press (1948).

24. D. E. Lea; Actions of Radiations on Living Cells; MacMillan Co. (1948).

25. E. Lorenz, W. E. Heston, and A. B. Eschenbrenner; Biological Studies in the Tolerance Range; Radiology 49, 274-8 (Sept. 1948).

26. W. Machle, E. Byer, and F. Gregorius; Berylliosis; Occupational Medicine 5, 671-683 (June 1948).

27. L. D. Marinelli, R. Brinckerhaff, and G. J. Hine; Average Energy of Beta-rays Emitted by Radioactive Isotopes; Rev. Mod. Physics 19, No. 1, 25 (Jan. 1947).

28. G. W. Morgan; Some Practical Considerations in Radiation Shielding; Isotopes Division Cir. B-4, A. E. C. (Nov. 1948).

29. K. Z. Morgan; Health Control and Nuclear Measurement; Unpublished Data from Lecture (1950).

30. G. J. Neary; Dose Measurements with Radium Beta-ray Applicators; Brit. J. Radiol. 19, 357-67 (Sept. 1946).

31. A. O. Nier; A Mass Spectrometer for Isotope and Gas Analysis; Rev. Sci. Inst. 18, 398 (1947).

32. R. Paterson; The Treatment of Malignant Disease by Radium and X-ray; Williams and Wilkins Co. (1949).

33. W. L. Peacock; Decay Scheme of $_{45}Ru^{106}$; Phys. Rev. 72, 104-9 (1947).

34. B. B. Rossi and H. H. Staub; Ionization Chambers and Counters, Experimental Techniques; McGraw-Hill (1949).

35. G. Schubert; Foundations and Results of Electron Therapy With a 6 Mev Betatron; Schweiz med. Wochschr. 80, 193-200 (Feb. 1950).

36. L. S. Skaggs; Depth Dose of Electrons from the Betatron; Radiology 53, 868-73 (Dec. 1949).

37. F. S. Spiers; The Influence of Energy Absorption and Electron Range on Dosage in Irradiated Bone; Brit. J. Radiol. 22, 521-33 (Sept. 1949).

38. F. W. Spiers; Dose Measurements in Beta-ray Therapy; Brit. J. Radiol. 19, 52 (Sept. 1946).

39. C. W. Wilson; Radium Therapy, Its Physical Aspects; Sherwood Press (1945).

40. H. Yagoda; Radioactive Measurements with Nuclear Emulsion; Wiley and Sons (1949).

41. K. Juris; Apparatus for the Therapeutic Application of the Primary Beta-rays of Radium (Beta-ray Howitzer); Acta Radiologica 20, 284-92 (1939). (In German).

Additional References

42. Chart of the Nuclides; General Electric Company (1950).

43. Lecture Notes, Health Physics Training; AECU-817 (Sept. 29, 1950).

44. Strontium Medical Applicator, Tracerlabs, Inc.; Tracerlog 28 (July 1950).